Will Perturbing Soil Moisture Improve Warm-Season Ensemble Forecasts? A Proof of Concept

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ABSTRACT

Current generation short-range ensemble forecast members tend to be unduly similar to each other, especially for components such as surface temperature and precipitation. One possible cause of this is a lack of perturbations to the land-surface state. In this experiment, a two-member ensemble of the Advanced Research Weather Research and Forecast (WRF/ARW) model was run from two different soil moisture analyses. One-day forecasts were conducted for six warm-season cases over the central United States with moderate soil moistures, both with explicit convection at 5-km grid spacing and with parameterized convection at 20-km grid spacing. Since changing the convective parameterization has previously been demonstrated to cause significant differences between ensemble forecast members, 20-km simulations were also conducted that were initialized with the same soil moisture but that used two different convective parameterizations as a reference.

At 5 km, the forecast differences due to changing the soil moisture were comparable to the differences in 20-km simulations with the same soil moisture but with a different convective parameterization. The differences of 20-km simulations from different soil moistures were occasionally large but typically smaller than the differences from changing the convective parameterization. Perturbing the state of the land surface for this version of WRF/ARW was thus judged to be likely to increase the spread of warm-season operational short-range ensemble forecasts of precipitation and surface temperature when soil moistures are moderate in value, especially if the ensemble is comprised of high-resolution members with explicit convection.

1. **Introduction**

A goal of ensemble forecasting is to produce sharp, reliable probabilistic weather forecasts. Unfortunately, it is quite common for ensemble forecasts to be at least somewhat unreliable, i.e., tallying situations when 20 percent probability was forecast, the event did not happen 20 percent of the time. When ensemble forecasts are compared subsequently against observations, too often these observations will lie outside the span of the forecasts (Hamill and Colucci 1997). This problem is commonly worse for variables such as surface temperature or precipitation (e.g., Mullen and Buizza 2001, Fig. 15) than for midtropospheric variables (e.g., Buizza et al. 2000, Fig. 7).

Why is there an inadequate range of forecasts, and why does it affect sensible-weather variables more than other aspects of the model state? There are many possible explanations, such as the inadequate resolution of ensemble members (Mullen and Buizza 2002, Szunyogh and Toth 2002, Buizza et al. 2003), suboptimal methods for generating initial conditions (Ehrendorfer and Tribbia 1997, Hamill et al. 2000, Hamill et al. 2003, Wang and Bishop 2003), and model biases related to problems in the parameterization of surface and boundary-layer effects and the diurnal cycle (e.g., Bright and Mullen 2002, Davis et al. 2003). While each of these may be very important, the one we choose to investigate here is the lack of perturbations to characteristics of the land-surface state. In most operational ensemble forecasts, the initial state of the atmosphere differs among ensemble members, but the initial state of the land surface is the same. If indeed the subsequent weather forecast is sensitive to perturbations to the land-surface state within the range of their uncertainty, then it may prove beneficial to perturb them in ensemble forecasts (Hamill 1997, Hamill and Colucci 1998).

In meteorological situations where ample solar radiation (insolation) reaches the ground, errors in the state of the land surface may affect the subsequent weather forecast. As the ground surface heats up during the day, sensible energy is transferred to the atmosphere, moisture evaporates from the soil or transpirates from plants (latent heating), and the soil below is heated. The partitioning of the available energy among sensible, latent, and ground heat fluxes depends on many variables, in particular soil moisture. Generally, the drier the soil, the smaller the daytime latent-heat flux, the larger the sensible-heat flux, the greater the warming of the air above, and the deeper the boundary layer (Philip 1957, Sasamori 1970, Pielke 2001). The partitioning also may be sensitive to a change in the roughness lengths (Zhang and Anthes 1982, Diak 1986) or other aspects such as soil textural characteristics (Ek and Cuenca 1994) or mis-specification of vegetation characteristics (Sellers et al. 1986, Xue et al. 1991).

There is a large body of literature demonstrating that mesoscale atmospheric circulations can be driven by regional differences in the land-surface state, circulations that in certain circumstances can determine where penetrative convection will develop (Ookouchi et al. 1984, Diak et al. 1986, Benjamin and Carlson 1986, Lanicci et al. 1987, Lakhtakia and Warner 1987, Yan and Anthes 1988, Chang and Wetzel 1991, Fast and McCorcle 1991, Betts et al. 1996, Chen et al. 2001). By extension, then, it is reasonable to hypothesize that an error in the land-surface state may change some of the details of the forecasts of penetrative convection, adding appropriate spread in warm-season ensemble forecasts of precipitation and near-surface variables.

The question we thus consider is whether realistic differences in the initial land-surface state will be large enough to substantially alter the location, timing, and intensity of convection in mesoscale, short-term numerical weather forecasts. If one member contains a best guess at the land-surface state and another member contains a realistic perturbed guess, will the two members produce substantially different forecasts? A synoptic evaluation of a dryline case (Trier et al. 2004) showed that changing from a coarse-resolution, less sophisticated soil moisture analysis to a fine-resolution, more sophisticated one increased the realism of the forecast convection. The timing and location of the convection was substantially different between the two simulations. Sensitivity to soil moisture was also demonstrated in Hamill and Colucci (1998) and Gallus and Segal (2000). Crook (1996) similarly demonstrated that minor changes to the low-level thermodynamic structure (of the sort we hypothesize could be introduced by changing the soil moisture) could dramatically alter convective forecasts.

The article will provide a proof of concept of the sensitivity of selected summertime weather forecasts to modest changes in the soil moisture state. Provided with two soil moisture analyses that provide different but equally valid estimates, will the subsequent weather forecasts differ? We examine short-range forecasts from six cases, two cases discussed in depth in this article and the remaining four in an online appendix. All cases had somewhat moderate analyzed soil moistures, the situation where sensitivity is typically largest. We will use the Weather-Research and Forecast (WRF) model with the Advanced Research (ARW) dynamical core at convection-resolving resolution (~5 km) and with parameterized convection (~20 km), and we compare the resulting differences in 2-m temperature and accumulated rainfall forecasts initialized with identical atmospheric conditions but different soil moistures. The comparison of simulations with resolved and unresolved convection should indicate whether the sensitivity to soil moisture may be accentuated or diminished with explicitly resolved convection. For the 20-km forecasts, we will also compare the differences stimulated by the different soil moistures to differences resulting from using distinct cumulus convection schemes, which previously has been shown to introduce sizeable differences in warm-season ensemble forecasts (Stensrud et al. 2000, Stensrud and Weiss 2002, Gallus 1999). This provides a standard of reference for the amount of variability introduced by perturbing the soil moisture.

This article will not provide an operational technique for generating 10 or 100 realistic soil moisture perturbations. This will be left for future research; our intent is to demonstrate that perturbing the soil moisture in operational short-range ensemble forecasts is likely to have beneficial effects on probabilistic precipitation and surface-temperature forecasts by increasing the spread. We also have chosen to demonstrate the sensitivity only in the first 24 h. The mechanisms for upscale propagation of errors beyond 24 h are by now well known (e.g., Tribbia and Baumhefner 2004 and references therein).

Section 2 will describe the WRF/ARW model setup and the soil moisture analyses. Section 3 will provide detailed results for two of the six cases; the remaining four are described in the online appendix. Section 4 provides conclusions.

2. **Experimental design**

a. WRF model configuration.

WRF is a non-hydrostatic, Eulerian mesoscale model (Klemp et al. 2000, Michalakes et al. 2001, Skamarock et al. 2001, Wicker and Skamarock 2002). The

ARW dynamical core will be used for all experiments. Simulations were run both at 20-km grid spacing and with an additional 5-km inner nest. 31 vertical levels were used. 20-km simulations used parameterized convection with a domain (the outer rectangle in Fig. 1) approximately encompassing the conterminous United States (US). The 5-km nested simulations used explicitly resolved convection; this grid spacing is comparable to that of other realistic simulations, such as the 4-km hurricane simulations in Davis et al. (2005). The location of the inner domains (Fig. 1) changed depending on the case.

The following approaches were used to represent physical processes in WRF/ARW: cloud microphysics were parameterized according to Lin (1983), longwave radiation parameterization was based on Mlawer et al. (1997), shortwave radiation was based on Dudhia (1989), and the Mellor-Yamada-Janjic approach was used for the boundary-layer parameterization (Janjic 1996, 2002). The NOAH land-surface model was used (Chen and Dudhia 2001) as well as the data sets of land-surface characteristics accompanying this model. For most experiments, the 20-km simulations used the Kain-Fritsch (KF) convective parameterization (Kain and Fritsch 1990, 1993). For comparison, some 20-km simulations also were performed with the Betts-Miller-Janjic (BMJ) convective parameterization (Betts 1986, Betts and Miller 1986, Janjic 1994).

The specific set of experiments that were performed will be described in section 2.c below.

b. Initial and boundary conditions.

The analyzed atmospheric and lateral boundary conditions were produced by the Eta Data Assimilation System, or "EDAS;" documentation is available at http://www.emc.ncep.noaa.gov/mmb/gcip.html . The data were archived on a Lambert-conformal grid with a nominal grid spacing of ~ 40 km. The modeling system was described in Rogers et al. (1995, 1996) and the archive is at the National Center for Atmospheric Research (dataset 609.2).

Two initial soil moisture states were used, both produced under the North American Land-Data Assimilation Scheme (LDAS) project described in Mitchell et al. (2004). Identical EDAS analyzed meteorological forcings (2-m temperature and specific humidity, 10-m wind components, surface pressure, downward longwave and shortwave radiation, and convective and total precipitation) and land-surface characteristics were used as inputs to the stand-alone NOAH land-surface model (LSM; Chen and Dudhia 2001) and the standalone MOSAIC LSM (Koster and Suarez 1996). One of the outputs of each LSM was a diagnosed profile of soil moisture. The atmospheric inputs to the LSMs were considered to be free of error, so biases in the forcing may have contributed to soil-moisture analysis biases. Before running WRF/ARW, the MOSAIC soil-moisture analyses were subsequently vertically integrated to the NOAH levels, the same levels used in WRF/ARW. The vertical integration conserved column total water content. Soil temperatures were the same for all simulations, taken from EDAS analyses.

While identical atmospheric forcings were provided both LSMs, the internal model physics and assumed vegetation characteristics were different enough so that over a long period of time, the soil moisture estimates grew increasingly different, each varying about their own climatological mean (Mahanama and Koster 2003). As will be shown in subsequent figures, in the 0-10 cm layer, MOSAIC was typically drier. Interestingly, in these formulation of these LSMs, the soil moisture was not considered to be a quantity that was important to analyze correctly in and of itself; what was important was that each LSM should provide reasonable accurate estimates of heat and moisture fluxes as part of their own modeling system, and each LSM achieved similarly reasonable fluxes from different soil moistures (Koster and Milly 1997).

Because NOAH and MOSAIC soil moistures evolved toward their own mean, a MOSAIC analyzed soil moisture state could potentially produce unrealistic forecast fluxes when used to initialize a forecast model with a NOAH LSM, as in our WRF/ARW experiments. In the simulations presented hereafter, the differences in midday, clear-sky sensible heat fluxes due to a change in soil moisture were typically 70 – 100 Wm^{-2}, a relatively large value. Results from Chen et al. (1996) compared differences between flux measurements and modeled fluxes using an earlier version of NOAH. There were several days when the flux differences were greater than 50 Wm^{-2}, even in a controlled setting where inputs to the LSM could be more carefully specified than in real-world NWP forecasts; hence 70 – 100 Wm^{-2} may be realistic. Also, the differences in our two chosen soil moisture estimates were meant to initiate differences in surface fluxes that could be attributable to any component of the land-surface state that may have been improperly estimated. As previously mentioned, errors in the roughness length, soil texture, vegetation characteristics, and so on can induce errors in forecast surface fluxes. We have chosen the simpler approach of perturbing one variable by a larger amount rather than many variables by somewhat smaller amounts. As will be shown later, however, the WRF/ARW is capable of responding very non-linearly, producing forecast differences even from much smaller perturbations. While the perturbation method demonstrated here is not ideal (e.g., it would be preferable to have perturbations centered on the presumed best analysis state), the perturbations used here should be adequate for testing to determine if there is a general sensitivity.

c. *Simulations performed.*

The set of five model simulations performed on each day are shown in Table 1. These five simulations included 20-km and nested 20- and 5-km simulations from the two different soil moisture states. The 20-km grid, encompassing the conterminous US (Fig. 1) used the Kain-Fritsch (KF) convective parameterization, while the inner grid used explicit convection. The two 5-km simulations were called “NOAH5” and “MOSAIC5,” the name reflecting the grid spacing and which soil moisture analysis was used. Additionally, the simulations were again run at 20 km without an inner domain; these simulations were named “NOAH20KF” and “MOSAIC20KF.” The reason for performing the simulations at 5 and 20 km was to determine if the sensitivity to soil moisture was qualitatively different with higher resolution and explicitly resolved convection. A final simulation was done at 20 km using the NOAH soil moisture analysis and the Betts-Miller-Janjic (BMJ) convection scheme, named “NOAH20BMJ.” The test at 20 km with the BMJ permitted a comparison of relative forecast differences from varying the soil moisture and the convective parameterization (Gallus 1999, Stensrud et al. 2000, Stensrud and Weiss 2002). Differences from changing convective parameterizations were used as a reference because they are now commonly varied in warm-season ensemble forecasts as a way of realistically increasing their spread (ibid).

Six different case days were examined, and on each day the forecasts were initialized at 1200 UTC and run for 24 h. Each case day involves a summertime simulation under weak or moderate flow, and in each there was an area of intense rainfall stimulated by surface-based convection. The cases were also selected to have soil moistures in the moderate range, and all of the cases selected were summertime cases. We examined these under the assumption the changes to weather forecasts due to a change in surface fluxes should be more evident under these conditions. We also chose to examine cases where the synoptic forcing was not particularly strong; again, one would not expect the soil moisture errors to stimulate much forecast error if an area is already covered by dense cloud and rain. The chosen days were 12 July 2001, 22 August 2001, 11 June 2002, 24 July 2002, 27 July 2002, and 11 August 2002. This article will examine 12 July 2001 and 24 July 2002; the remaining cases are described in the online appendix.

3. **Results**.

a. 12 July 2001

Figure 2a shows the sea-level pressure and the 500 hPa geopotential height used to initialize this model run. A broad ridge at 500 hPa was evident with its axis along the Rockies, with relatively weak flow through most of the center of the country. A surface-pressure trough extended from the low-pressure system east of Maine, along the Atlantic seaboard, and then back through central Mississippi, Oklahoma, and into eastern Montana. The 24-h analyzed precipitation in Fig. 2b (taken from the ~32 km North American Regional Reanalysis, Mesinger et al. 2005) shows an extensive area of rainfall from southern Missouri south to the Gulf Coast, with more precipitation in western Kansas and eastern Colorado. For this experiment, we located the fine-mesh domain to cover the precipitation feature in the Mississippi River Valley (Fig. 1), where there was a maximum of greater than 40 mm of rainfall in central Arkansas and western Mississippi, as well as scattered reports of small hail and damaging winds. The NOAH soil moisture analysis (Fig. 2c) in this region showed generally moderate soil moisture amounts, though moister areas were found in western Missouri and southern Louisiana. Relative to NOAH, the top-layer MOSAIC soil moisture was more commonly drier (Fig 2d).

Consider the NOAH5 simulated rainfall in Fig, 2e, accumulated over 24 h. The pattern of heavy rainfall was in a similar region to where heavy rain was observed, though the forecast maximum in central Arkansas was slightly east of where it was observed. Figure 2f shows the difference in accumulated precipitation between the MOSAIC5 and NOAH5 simulations. The precipitation differences were often quite large in magnitude, often 20 mm or more. The general region where the precipitation occurred was similar, but the exact location of the convective cells often differed by ~50 km. In some situations, this may have led to a somewhat better forecast. For example, the MOSAIC5 simulation was somewhat moister further west in Arkansas and produced more precipitation in central and southern Mississippi, as was observed. Considering the 12-h 2-m temperature forecasts at 0000 UTC 13 July 2001 (Fig. 2g), a strong temperature contrast was evident in central Arkansas, delineating the boundary at that time between the convectively modified air to the north (Fig. 3j) and the pre-convective environment to the south. Figure 2h shows that in some areas there were as much as 5 C differences between the simulated 2-m temperatures in the MOSAIC5 and NOAH5 runs. Most notably, due to differences in the intensity of convection over Louisiana and Mississippi

(Fig. 3k), there were relatively large differences in the 2-m temperature forecasts, with the areas affected by convectively initiated cold pools differing between the simulations.

Figure 3 shows the 3-hourly accumulations in the NOAH5 simulation as well as the differences between MOSAIC5 and NOAH5. An additional set of simulations was also conducted, whereby the differences in soil moisture were scaled down to 10 percent of their original size, i.e., the MOSAIC5 soil moisture was replaced by the NOAH5 soil moisture plus 10 percent of the difference between MOSAIC5 and NOAH5, and the precipitation differences are shown for this case as well. Interestingly, the differences were nearly as large for the simulation with the 90 percent smaller soil moisture perturbation. Even with the smaller perturbation, convection triggered in slightly different locations. Thus the response to initial perturbations can be strongly non-linear in the presence of convection. As soon as convection was initiated at different grid points in the two simulations, regardless of whether this happened as a consequence of a small or large soil moisture perturbation, the pair of precipitation forecasts quickly became very different. This may exemplify the rapid error growth up from the small scales posited by Lorenz (1969).

The simulations were also performed at 20 km grid spacing using the Kain-Fritsch convective parameterization (NOAH20KF and MOSAIC20KF). Figure 4 provides the precipitation and temperature forecast information for these simulations. Figure 4a shows that the NOAH20KF precipitation in Arkansas was located ~100-150 km to the east of the band from the NOAH5 simulation in Fig. 2e. The highest precipitation totals from MOSAIC20KF were displaced to the west of the band in the NOAH20KF (Fig. 4b). Outside of the region around Memphis, Tennessee, where the two simulations were very different, the precipitation differences were typically smaller than the differences at 5 km with explicit convection. The temperature differences were smaller, too (Fig. 4c-d) , and didn't produce large areas of differences caused by changing cold pool locations.

Consider the general sensitivity to the soil moisture compared to the sensitivity due to choice of convective parameterization. Figure 5a shows the precipitation from the NOAH20KF and NOAH20BMJ simulations. The differences in precipitation amount and 2-m temperature forecasts are shown in Figures 5 b-c. The differences in precipitation were comparable in magnitude to the differences between the NOAH5 and MOSAIC5 simulations (Fig. 2f), but here the differences tended to be much larger in scale; the NOAH20BMJ produced much less widespread convection over the Gulf Coast and up the Atlantic seaboard than the NOAH20KF. Temperature differences of 1-2 K or larger were quite widespread, related to differences in the areas where convection was forecast and the subsequent parameterization of moist downdrafts in the two schemes (see also Wang and Seaman 1997).

This case demonstrates that sizeable differences in precipitation and surface temperatures can be induced by differences in the soil moisture in WRF/ARW. The soil moisture did not radically change the area where convection occurred, but differences at individual grid points were often very large due to small displacements of the convective elements.

b. 24 July 2002

For this case, at 1200 UTC, a weak surface ridge extended from Wyoming to western Texas (Fig. 6a), and a trough of low pressure extended southeast from eastern

Montana, with a region of strong southerly flow over the eastern Dakotas. Zonal flow predominated at 500 hPa over the northern tier of states. Precipitation was observed in the northern Great Plains states, along the Texas border with Oklahoma and Louisiana, along the Florida Gulf Coast, and up through the Carolinas (Fig. 6b). Several tornadoes occurred in central Nebraska on this day, and there were widespread reports of hail and damaging wind in Nebraska and the Dakotas. We located our 5-km domain to cover the precipitation maximum in the northern Great Plains states (Fig. 1). The top-layer NOAH analyzed soil moisture (Fig. 6c) shows modestly moist soils east of central Iowa, with drier soils to the west. The top-layer MOSAIC soil moisture was even drier across much of the Great Plains (Fig. 6d), with a small patch of wetter soil occurring over northwest Illinois. However, over many parts of Nebraska, the subsoil layers were moister in MOSAIC than in NOAH (not shown).

The NOAH5 simulation produced a band of intense precipitation (Fig. 6e) over the border of Iowa and Minnesota. The highest accumulated forecast totals were in excess of 80 mm. The precipitation maximum was forecast to the east of where it was actually observed (Fig. 6b) and forecast more than observed. Comparing the difference between the MOSAIC5 and NOAH5 simulations (Fig. 6f), the MOSAIC5 simulation produced a more intense band to the northeast of the band in NOAH5, a more intense second band through central-northern Minnesota, and a more intense third band in northwest Iowa, closer to the observed maxima. Compared to the previous 12 July 2001 case, the precipitation differences were larger in scale.

The NOAH5 simulation produced a strong 2-m temperature gradient at 12 h in northeast Nebraska, dividing the convectively modified and pre-convective air masses.

The MOSAIC5 simulation was slightly warmer (Fig. 6h) over southwest Minnesota and in a NW-SE band from SE South Dakota to NW Iowa, reflecting a slightly delayed southwesterly propagation of the cold pool in the MOSAIC5 simulation. Elsewhere, it was as much as 2-5 C cooler than the NOAH forecast over a wide area in eastern Kansas, Nebraska, South Dakota, and North Dakota. The lower temperatures in the MOSAIC5 were attributable to less sensible and more latent heating as a result of the higher sub-surface soil moistures in MOSAIC.

Figure 7a shows the forecast 24-h precipitation totals for the NOAH20KF simulation. The highest forecast accumulations were 40 - 60 mm, heavier than observed (Fig. 6b) but somewhat lighter than the 5-km forecast (Fig. 6e) and closer to the position of the observed maximum. Figure 7b shows that the maximum from the MOSAIC20KF forecast occurred to the east of the maximum in NOAH20KF, with generally lighter amounts elsewhere. The differences again were relatively larger in scale than in the 12 July 2001 case. The 2-m temperature forecast in Fig. 7c was similar to that from the NOAH5 (Fig. 6g). Temperature differences of 1 C or larger were common, even in areas outside of the region of convection.

The precipitation forecast differences (Fig. 8b) resulting from the use of the BMJ parameterization (Fig. 8a) were rather similar to the differences introduced by varying the soil moisture, though somewhat lesser in magnitude in this case. Surface-temperature differences (Fig. 8c) were also a bit smaller than those introduced by varying the soil moisture.

The remaining four cases are described in the online appendix.

c. Synthesis of statistics from all cases

Figure 9 presents the statistics on how much variability was introduced to 24-h precipitation and 12-h surface-temperature forecasts by varying the soil moisture or the convective parameterization. We consider the MOSAIC5-NOAH5, MOSAIC20KF-NOAH20KF, and the NOAH20BMJ-NOAH20KF differences, stratified by the grid-point precipitation amount of the control forecasts in each case (NOAH5, NOAH20KF, and NOAH20KF, respectively). In the case of MOSAIC5-NOAH5, the gridded forecasts were averaged to 20 km, so the statistics were done on a comparable grid; on the figure, these data are labeled "$<$MOSAIC5-NOAH5$>_{20}$". All data are presented only over the region of the inner domain using the six cases, two from this article and four from the online appendix.

From Fig. 9, we see that when little or no rain was forecast in the control, typically changing the soil moisture did not change this. When heavy rain was forecast, then relatively large changes commonly occurred as a result of changing soil moisture or convective parameterization. The changes at 5 km due to changing the soil moisture were comparable to the changes at 20 km due to varying the convective parameterization. The precipitation changes in the 20-km simulations due to changing the soil moisture were smaller than in the 5-km simulations, though from the individual maps, the reader can see that the effects were often large in several of the cases. For surface temperature forecasts (Fig. 9b), approximately 10 percent of the grid points had their 12-h forecast of surface temperature changed by 1 K or more in each sensitivity study, indicating that the soil moisture uncertainty in WRF/ARW can be a source of short-range surface temperature forecast variability in some regions.

Examining the frequency at which the precipitation amount forecasts were issued (Fig. 10), the BMJ parameterization produced heavy precipitation less frequently than the KF. The explicit convection forecasts at 5 km produced more zero and more heavy precipitation amounts than the 20-km parameterized convection but fewer intermediate amounts. Changing the soil moisture initial condition did not change the precipitation frequency distribution very much (not shown); the apparent "bias" in Fig. 9a of $\langle$MOSAIC5-NOAH5$\rangle_{20}$ at high precipitation amounts is illusory. What this diagram indicates is that in situations where NOAH5 forecast very heavy precipitation, typically MOSAIC5 forecast less. However, there were many cases when NOAH5 forecast lesser amounts and much heavier rain was forecast in MOSAIC5 (hence the outlying dots are skewed toward heavier MOSAIC5 precipitation amounts).

Overall, these results confirm the impression presented by studying the weather maps that perturbing the soil moisture did not tend to alter the general region where convection was forecast, but it introduced variability in the amount, with more variability introduced in regions where the control forecast large amounts. The result of not altering the region where convection was forecast is somewhat different than a result presented in a preliminary sensitivity study (Hamill and Colucci 1998, Fig. 3 a-b). In one case study there, an intense band of precipitation was forecast from one soil moisture, while nearly none was forecast from a slightly different soil moisture. Perhaps if we had examined more than the six cases presented here, we would have seen similar examples of radically different precipitation forecasts, where convection was triggered in one simulation but not another.

4. **Conclusions**.

In this study, we examined the WRF/ARW model's short-range warm-season temperature and precipitation forecast sensitivity due to changing the source of the soil moisture analysis. Our hypothesis was that in some situations, a modest change in the soil moisture could substantially change the short-range weather forecast by altering the timing and location of convective precipitation. If this was the case, then perturbing the soil moistures may add some spread to short-range ensemble weather forecasts, which typically have member forecasts that are unduly similar.

The results presented here suggest that short-term temperature and precipitation forecasts can indeed be changed as a consequence of changing the soil moisture. The changes to 5-km forecasts due to soil moisture differences were almost as large as the changes to 20-km forecasts due to using an alternate convective parameterization, previously determined to be a large source of uncertainty in ensemble forecasts. Changing the soil moisture of 20-km forecasts introduced less variability on average, but for several of the case days, the differences between the simulations were quite large.

We expect then that perturbing soil moisture initial conditions should have a beneficial impact on the skill of short-range probabilistic forecasts of surface temperature and precipitation during the warm season. While this study did not address how to generate a large ensemble of these differences, generating a perturbation methodology is hardly an insurmountable problem. Perhaps perturbations could be generated by randomly sampling from a time series of differences between soil moisture analyses from different sources, or perhaps the initial conditions from an ensemble Kalman filter of soil moisture analyses could be used (e.g., Reichle et al. 2002 ab).

In this study we specifically picked soil moisture and synoptic conditions where the sensitivity would be expected to be largest. For example, we chose summer cases because perturbing soil moisture should have a much greater effect with stronger insolation. We also chose cases where the soil moisture was typically moderate in value, for if the soil is very moist, a small change in soil moisture will not radically change the amount of vapor flux to the atmosphere (similarly so when the soil is very dry). We also chose cases where the precipitation could be expected to be initiated by surface-based convection, not driven primarily by large-scale forcing. Hence, the rather large sensitivity demonstrated here can be expected to significantly increase the spread of ensemble surface temperature and precipitation forecasts only in certain warm-season situations.

It is also possible that the sensitivity we have demonstrated with this particular version of WRF/ARW may not be representative of the sensitivity of WRF/ARW with different parameterizations or the sensitivity from a completely different modeling system. However, there is reason to believe our results may be general. In a previous study with MM5 with different parameterizations (Hamill and Colucci 1998), we found a similar sensitivity. Further, Crook (1996) found a precipitation forecast sensitivity to low-level temperature and moisture (which could be produced by soil-moisture changes) in a completely different model. Still, for operational ensemble model developers, it would be wise to verify a sensitivity in their forecast model before implementing soil moisture perturbations.

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List of Figure Captions

Figure 1: Outer and inner domains used in WRF/ARW experiment. Outer domain, common to all cases, is ~20 km grid spacing, and interior domains ~ 5 km. Domain (a) was used for the 12 July 2001 case, (b) for the 24 July 2002 case.

Figure 2: Data for 24-h simulation initialized on 1200 UTC 12 July 2001. (a) Analyzed mean sea-level pressure and 500 hPa geopotential height, (b) analyzed 24-h rainfall in subsequent 24 h, (c) NOAH analyzed soil moisture in the 0-10 cm layer, (d) difference between NOAH and MOSAIC analyzed soil moisture in this layer. Subsequent panels denote the forecast data from the 5-km simulations. (e) Accumulated 24-h forecast precipitation from NOAH5, (f) 24-h accumulated difference in precipitation between MOSAIC5 and NOAH5 simulations, (g) 12-h forecast 2-m temperature from NOAH5 simulation, and (h) 12-h forecast 2-m temperature difference between MOSAIC5 and NOAH5 simulations.

Figure 3: 3-hourly accumulated precipitation (panels a,d,g, and j) from NOAH5 simulation for 12 July 2001 case. 3-hourly accumulated precipitation differences between MOSAIC5 and NOAH5 simulations (panels b, e, h, and k). 3-hourly accumulated precipitation differences between scaled MOSAIC5 and NOAH5 simulations (panels c, f, i, and l), where the MOSAIC5 initial soil moisture has been replaced by an initial soil moisture that consists of the NOAH5 initial soil moisture plus 10 percent of the difference between MOSAIC5 and NOAH5 initial soil moistures.

Figure 4: (a) 24-h forecast accumulated precipitation from NOAH20KF simulation for 12 July 2001 case. (b) Difference in 24-h accumulated precipitation between MOSAIC20KF and NOAH20KF simulations. (c) 12-h forecast of 2-m temperature from NOAH20KF simulation, and (d) Difference in 12-h forecast of 2-m temperature between MOSAIC20KF and NOAH20KF simulations.

Figure 5: (a) 24-h forecast accumulated precipitation from NOAH20BMJ simulation for 12 July 2001 case. (b) Difference in 24-h accumulated precipitation between NOAH20BMJ and NOAH20KF simulations. (c) Difference in 12-h forecast of 2-m temperature between NOAH20BMJ and NOAH20KF simulations.

Figure 6: As in Figure 2, but for 24 July 2002.

Figure 7: As in Figure 4, but for 24 July 2002.

Figure 8: As in Figure 5, but 24 July 2002.

Figure 9: Box and whiskers plot of differences in (a) precipitation and (b) temperature forecasts induced by changing soil moisture at 5 or 20 km grid spacing, or the 20-km convective parameterization. In panel (a), the box and whisker diagrams indicate the 1st and 99th percentiles of the differences (dots), the 5th and 95th percentiles (error bars), the 33rd and 67th percentiles (tops and bottoms of colored boxes), and the 50th percentile (black line in middle of colored box). For precipitation, the differences are stratified by the 24-h precipitation amount of the control forecast (NOAH5 or NOAH20KF) in the inner domain. For temperature, the statistics are accumulated over all grid points in the inner domain. Data beyond plotting range: the 1st and 99th percentiles for the

precipitation difference of MOSAIC5 – NOAH5 when the control is > 40 mm is -97.1 and 84.7; for NOAH20BMJ – NOAH20KF is -91.9 and 82.0. For temperature, 1st percentile of the MOSAIC20KF – NOAH20KF is -15.8 C.

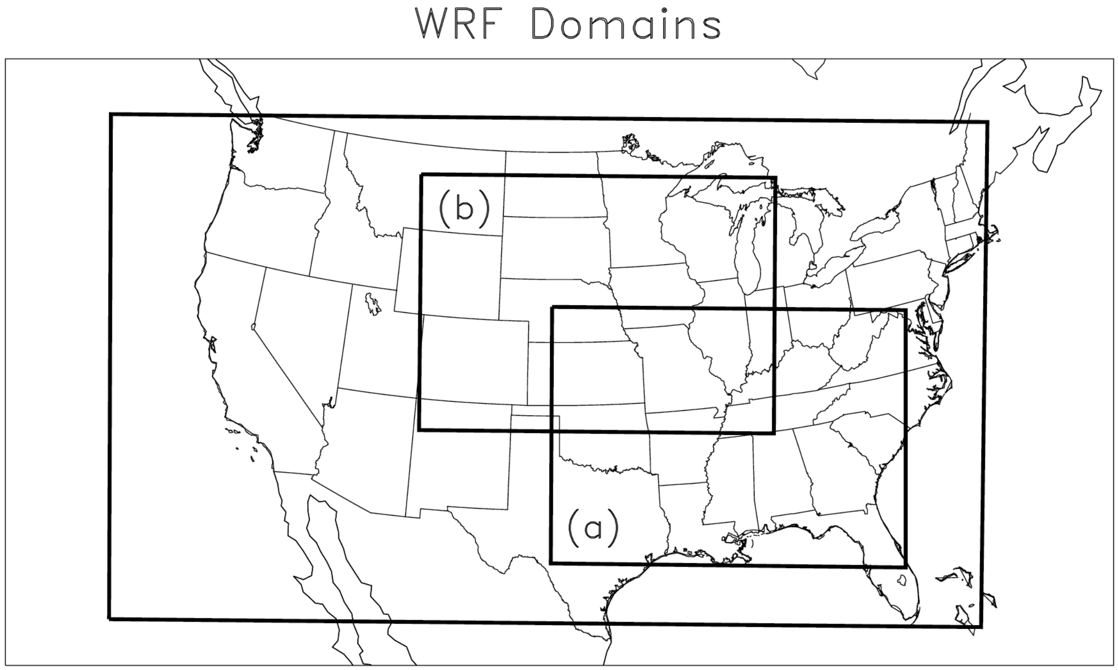
Figure 10: Frequency of 24-h precipitation amounts in inner domain for NOAH5, NOAH20KF, and NOAH20BMJ forecasts.

List of Table Captions

Table 1: List of names of experiments performed, as well as the associated soil moisture analysis used for initialization and the resolution and type of convective parameterization.

Experiment Name	Soil Analysis	Resolution	Convective Parameterization
NOAH5	NOAH	5 km	explicit
MOSAIC5	MOSAIC	5 km	explicit
NOAH20KF	NOAH	20 km	Kain-Fritsch
MOSAIC20KF	MOSAIC	20 km	Kain-Fritsch
NOAH20BMJ	NOAH	20 km	Betts-Miller-Janjic

Table 1: List of names of experiments performed, as well as the associated soil moisture analysis used for initialization and the resolution and type of convective parameterization.



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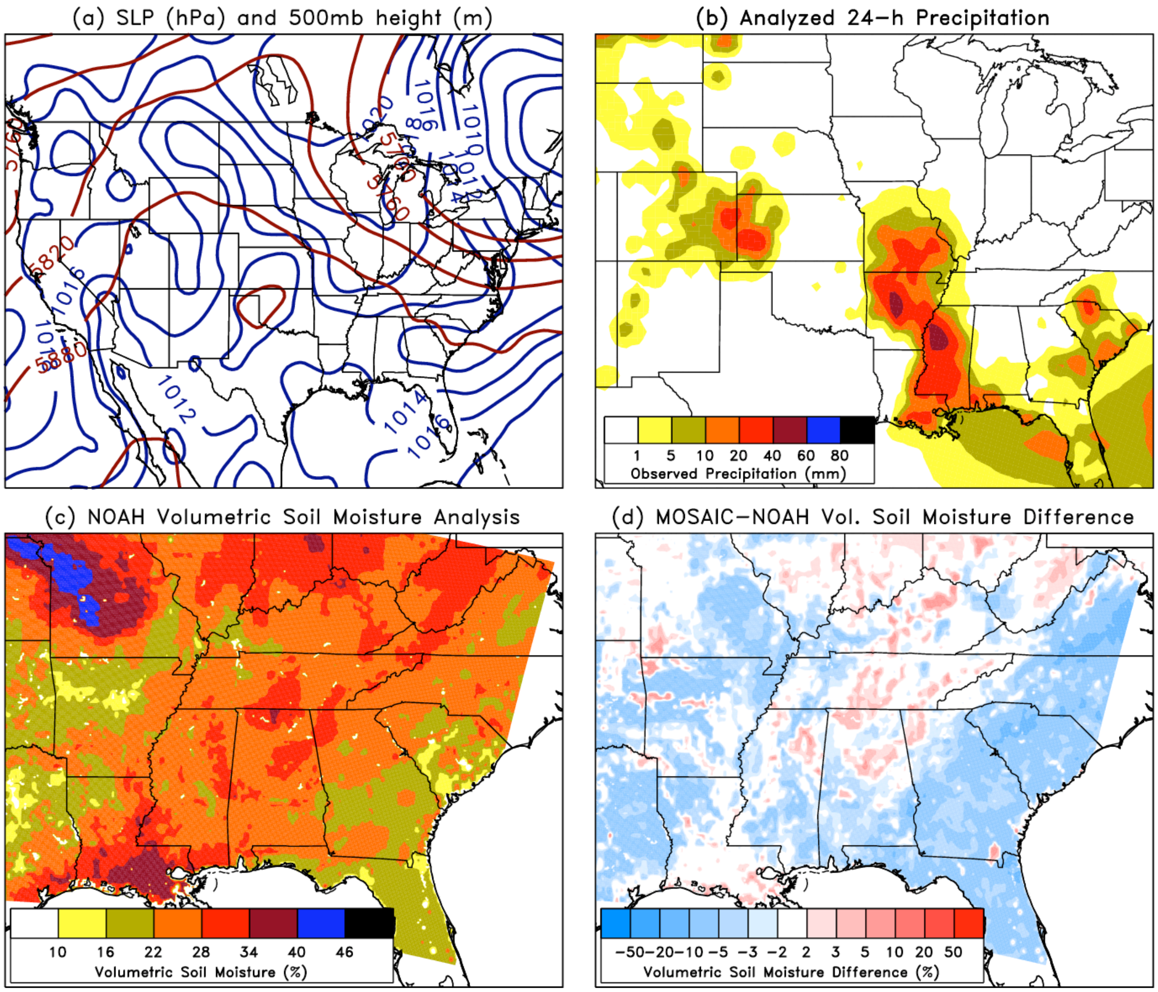
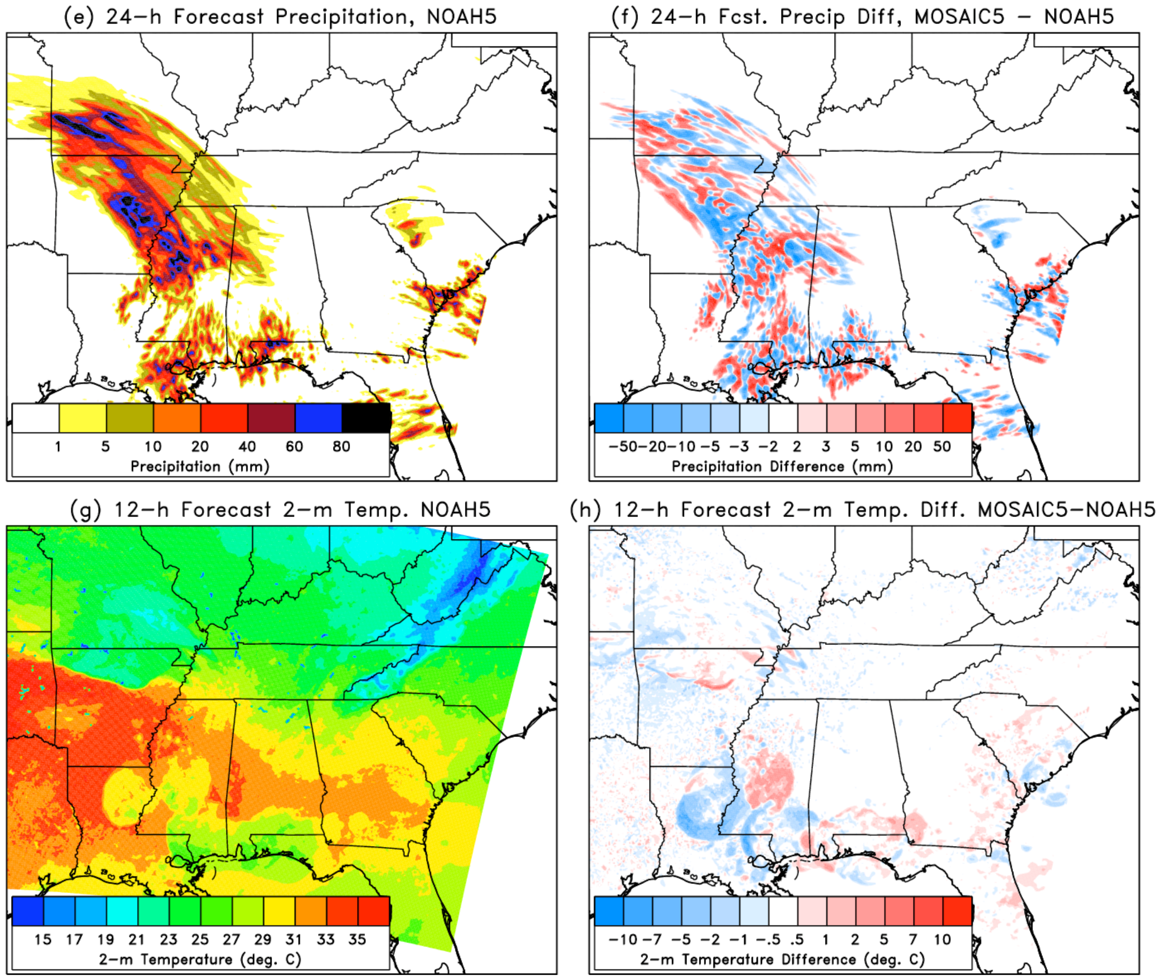


Figure 2: (see caption on next page)



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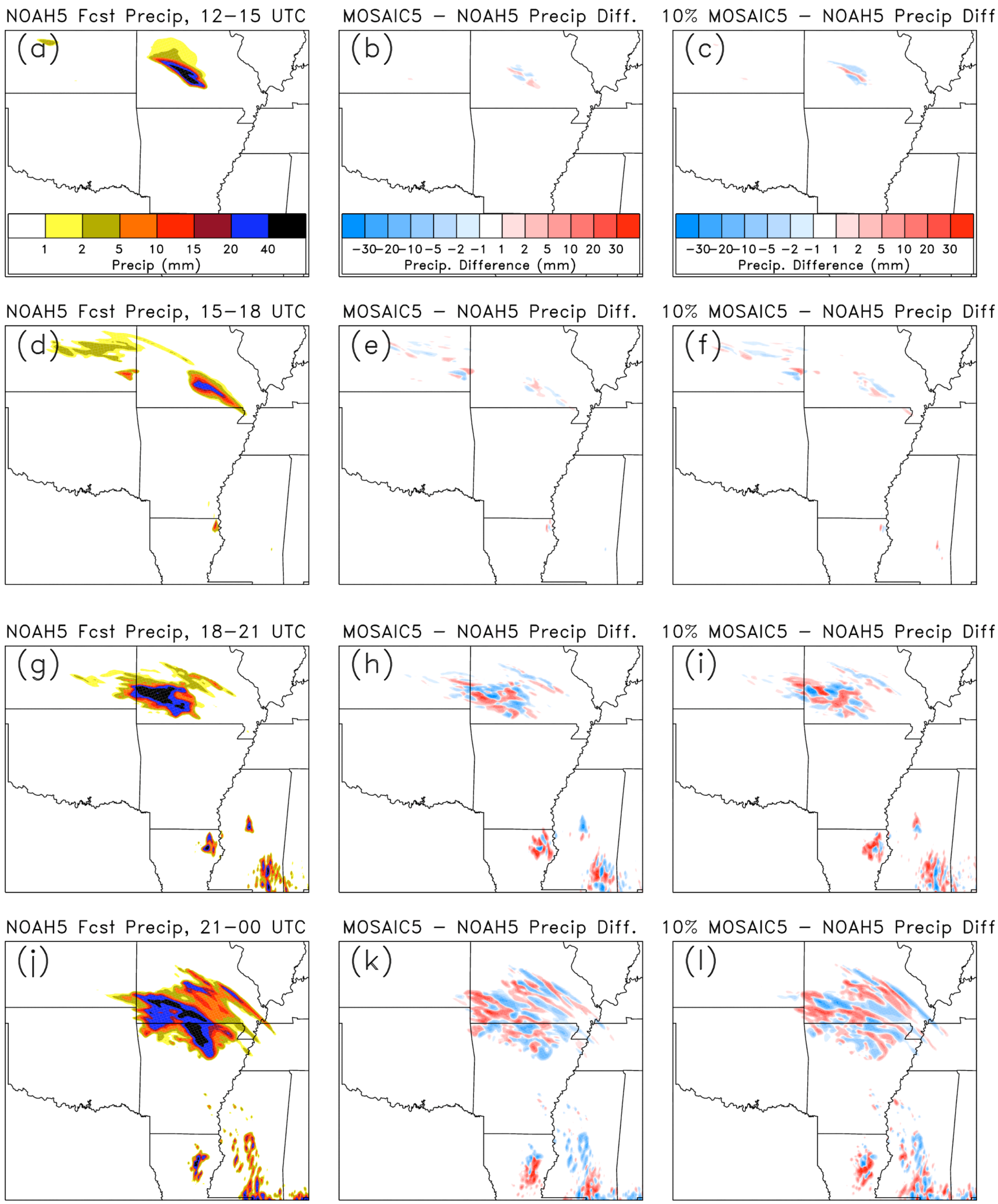

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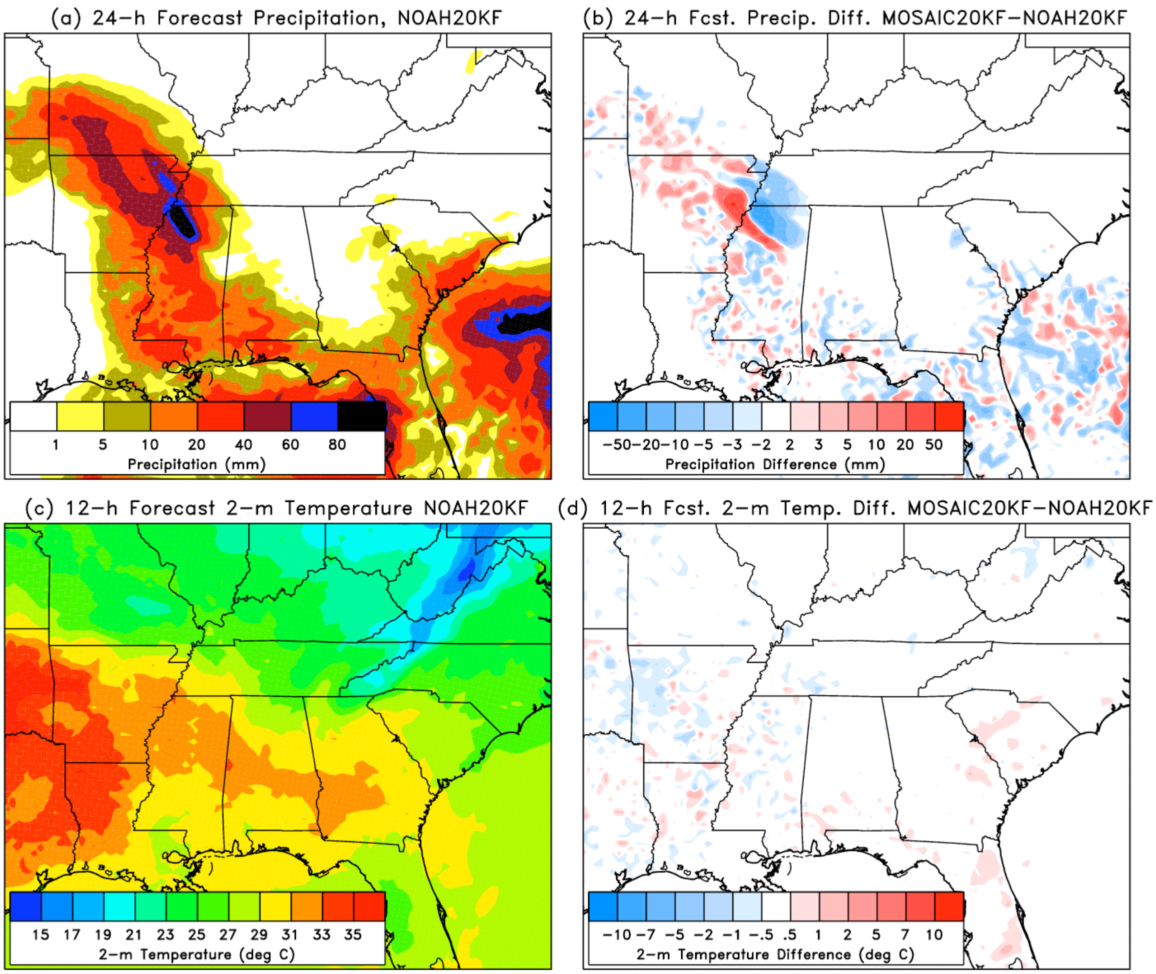

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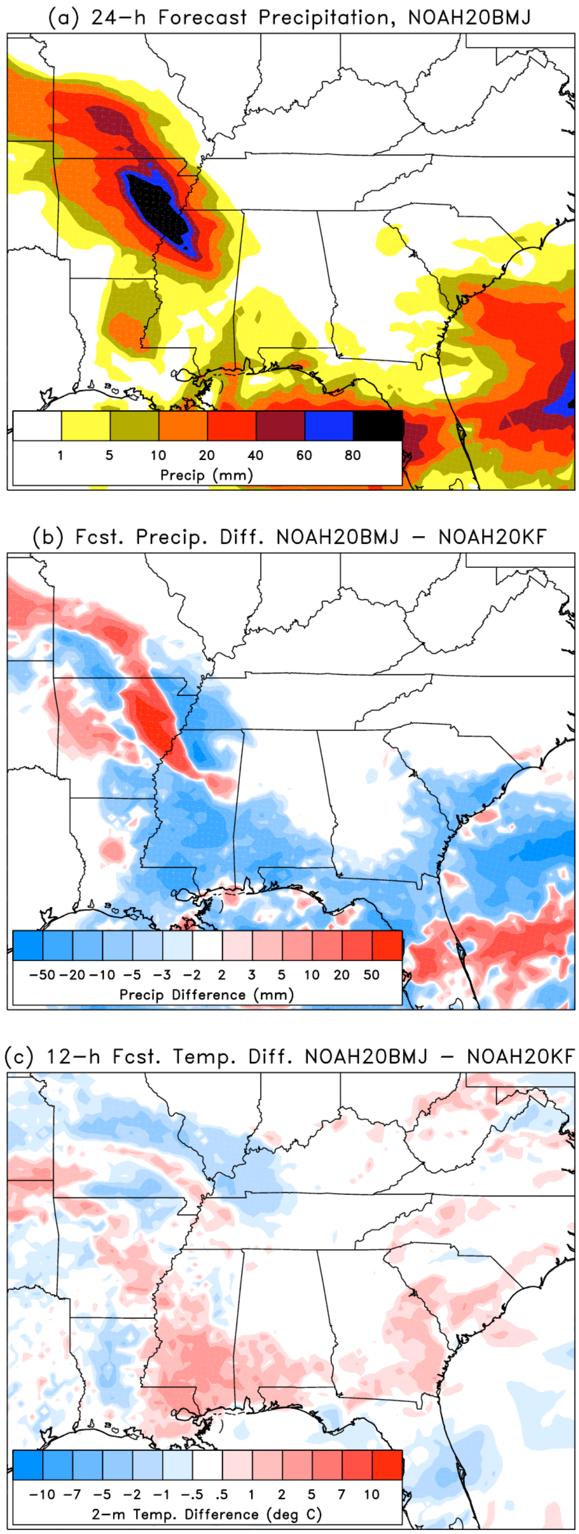

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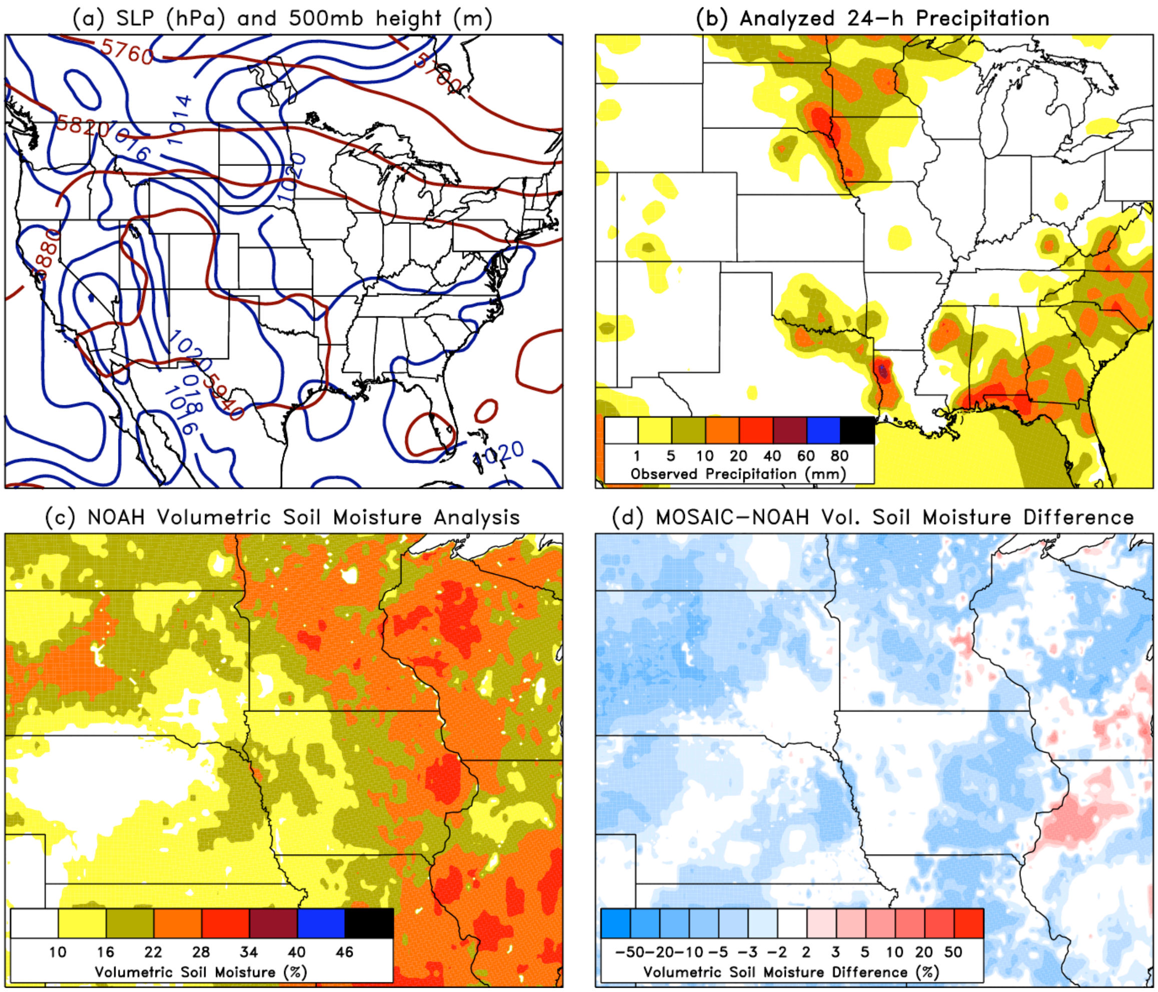

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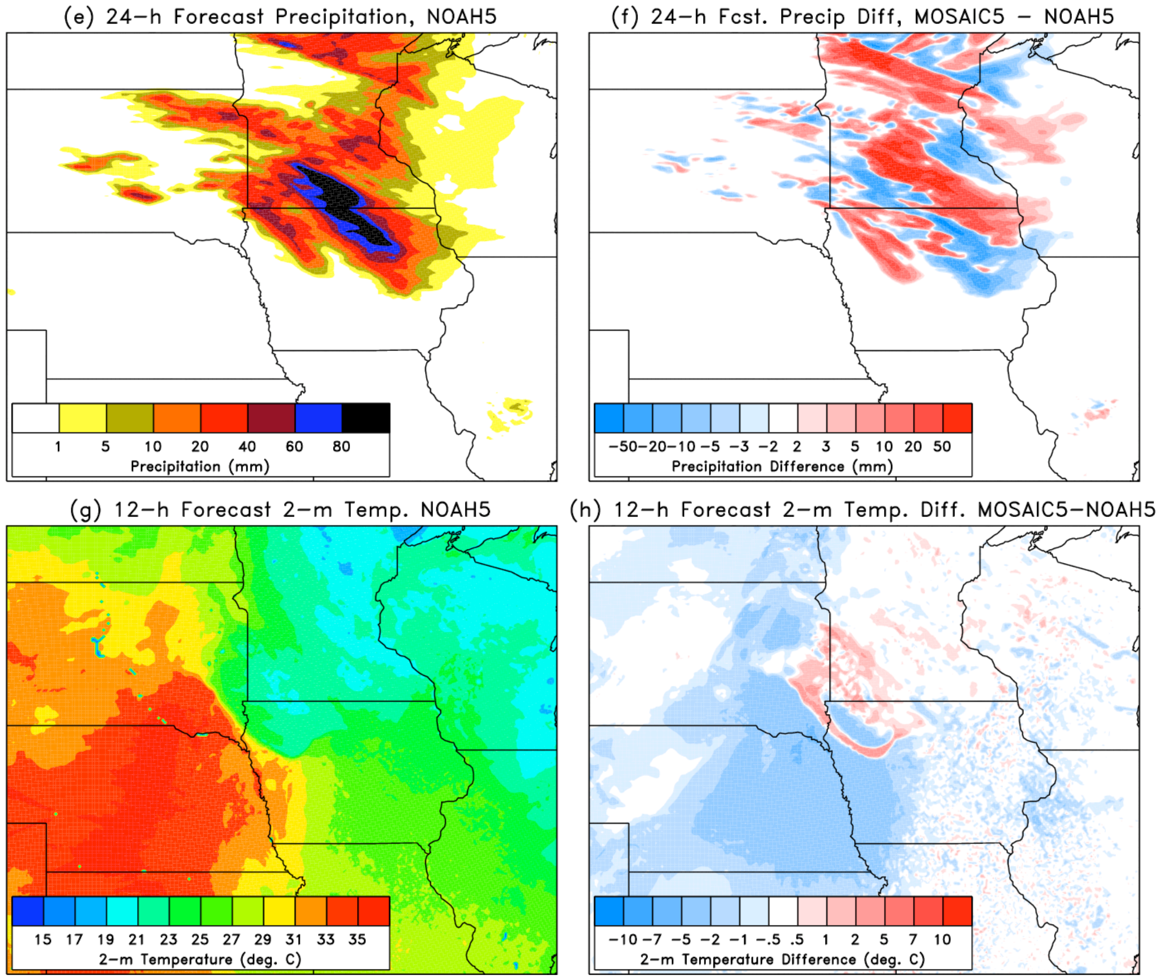

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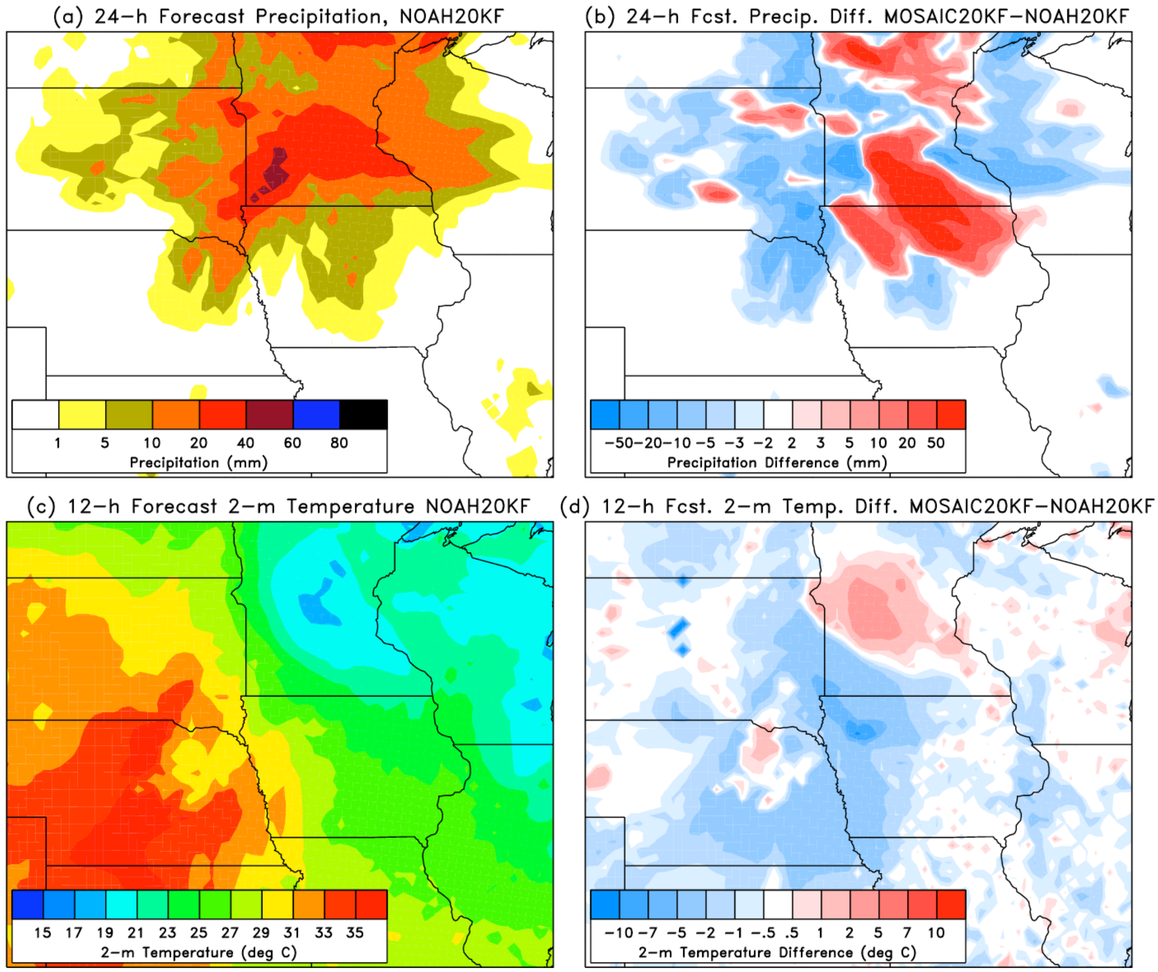

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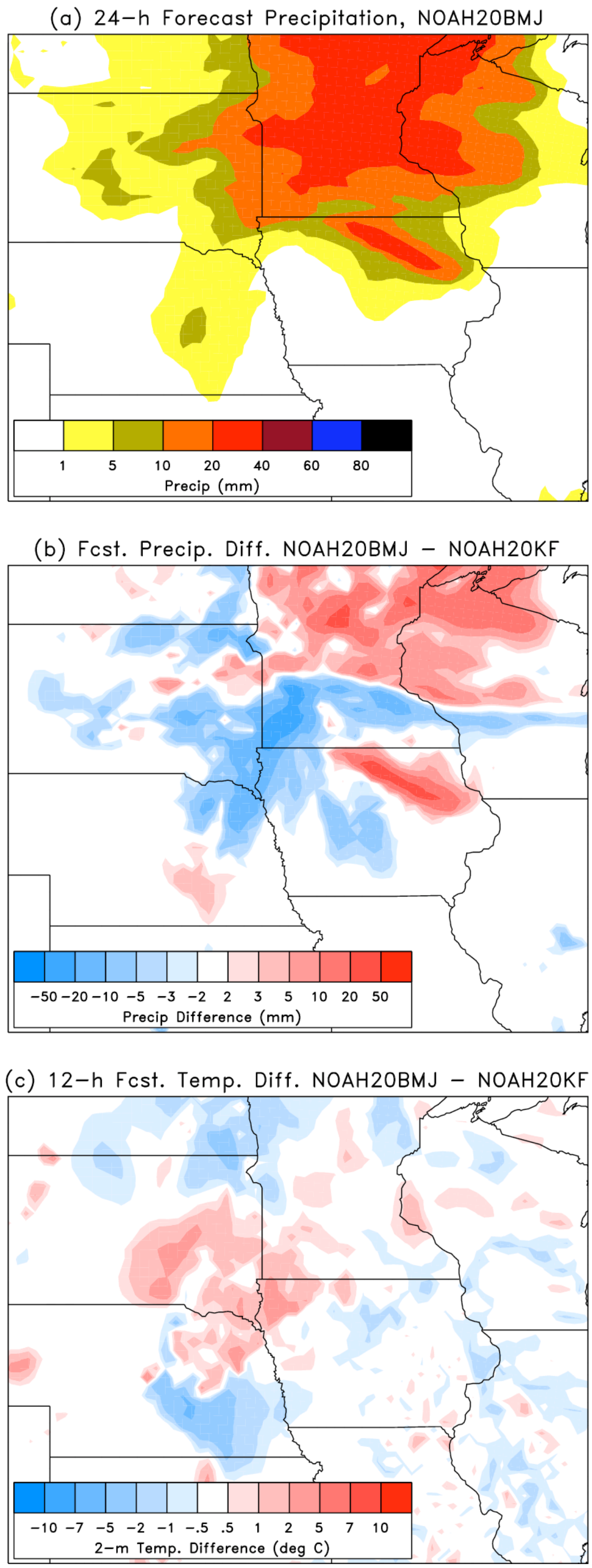

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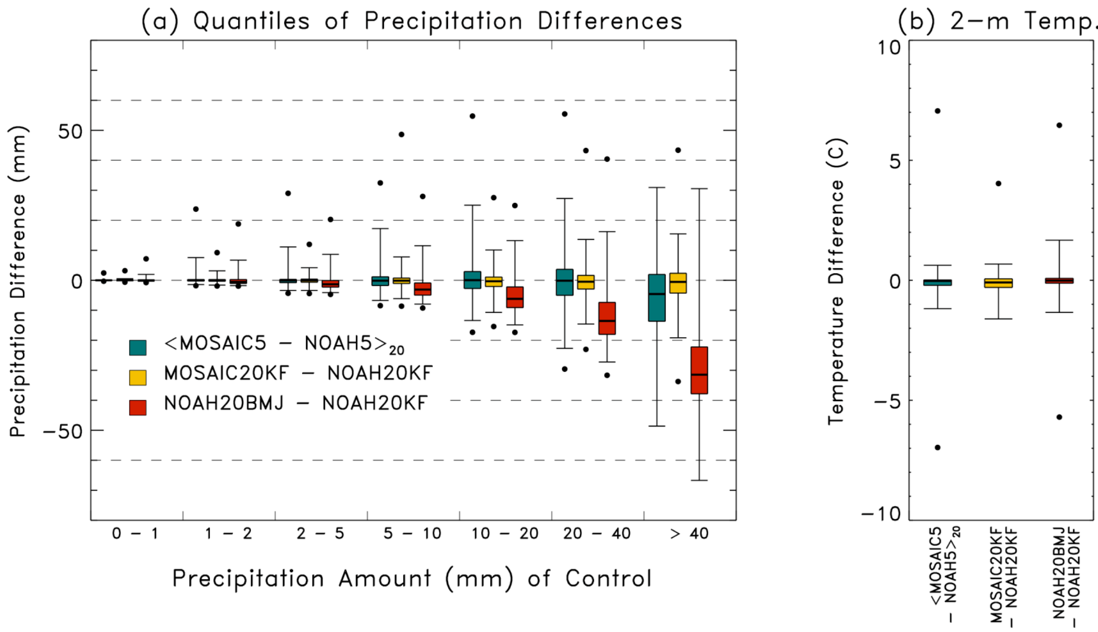

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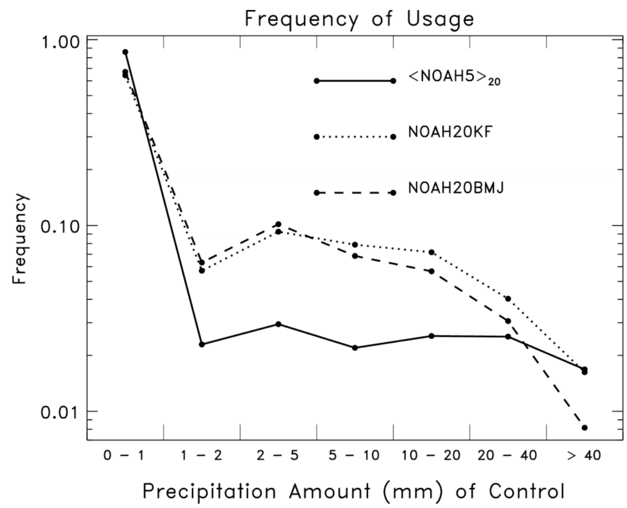

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